The effect of soil saturation on the heat transfer rate in a controlled environment for application to ground source heat pumps

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The Effect of Soil Saturation on the Heat Transfer Rate in a Controlled Environment for Application to
Ground Source Heat Pumps

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Nomenclature

$\dot{Q}_{\text{cond}}$: heat conduction (kW)

$k$: thermal conductivity ($\frac{W}{m \cdot K}$)

$A$: area perpendicular to the direction of the heat transfer (m)

$T_1$: highest temperature (K)

$T_2$: lowest temperature (K)

$\Delta x$: length through which heat transfer is taking place (m)

$\dot{Q}$: general heat transfer rate (kW)

$\dot{m}$: mass flow rate ($\frac{kg}{s}$)

$c_p$: specific heat ($\frac{kJ}{kg \cdot K}$)

$T_{\text{in}}$: temperature into the system (K)

$T_{\text{out}}$: temperature out of system (K)

$COP$: coefficient of performance (dimensionless)

$W_C$: work of the compressor (kW)

$\dot{Q}_L$: rate of heat transfer being pulled from the heat reservoir (kW)
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**Introduction and Literature Review**

With the current worldwide push for more environmentally friendly advancements in technology, the field of heating and cooling was bound to make headway due to its large impact on the environment. Many of the conventional systems used to heat and cool add vast amounts of pollution to the air. To counteract this pollution issue, technology has progressed considerably in the realm of heating and cooling. While there are quite a few competing systems in this field, Ground Source Heat Pumps (GSHPs) are quickly proving their worth when it comes to systems that are both environmentally friendly and efficient. When compared with systems such as conventional air conditioning, gas furnaces, and propane furnaces, GSHPs surpass them all.

When comparing these technologies, it is important to consider environmental impact, efficiency, availability of resources, and cost. These factors are closely related. If the efficiency is greater, the environmental impact is decreased along with the cost and fewer resources will be needed. If a system is largely dependent on a resource, there’s a good chance that it will not be applicable in a lot of applications. For example, heating systems that rely on coal or propane have to have the material transported. This creates an increase in cost. These materials are also nonrenewable resources. This makes these systems unrealistic in the long term both due to their impact on the environment and the lack of resource sustainability.

Solar systems initially seem like a great idea. They work off of an ample resource that most areas have. While it could be an addition to a system to increase efficiency at times, in some places the sunlight is not always reliable. Some areas are not positioned to receive direct sun, and even if they are, the sun may be behind clouds. While solar may have a lot of positives, it is too dependent on weather to make it a reliable source in most places. Water source heat pumps are similar to GSHPs with even better results. However, they need larger bodies of water to function. Only a small portion of the population would be able to take advantage of such a heat pump. However, GSHPs simply need the ground and electricity which a large majority of mankind has access to.

The differences in environmental impact are staggering. Table 1 below [1] shows the differences in the $CO_2$ emissions between the different methods. It is important to note, that in order to decrease the emissions to zero, the electricity needed must be generated in an environmentally friendly way. If the electricity is generated by burning fossil fuels it will counteract some of the $CO_2$ emissions that the GSHP is preventing [2, 3]. If the power is generated through wind, solar, or water, as Table 1 below reveals, the $CO_2$ emissions can reach 0. If we use the GSHP without green electricity, the GSHP still remains one of the cleaner systems, but there is a significant increase in $CO_2$ emissions.

<table>
<thead>
<tr>
<th>System</th>
<th>$CO_2$ emissions (kg $CO_2$/kWh heat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Fired Boiler</td>
<td>0.45 – 0.48</td>
</tr>
<tr>
<td>Gas Fired Boiler</td>
<td>0.26 – 0.31</td>
</tr>
<tr>
<td>Condensing Gas Boiler + Low Temperature System</td>
<td>0.21</td>
</tr>
<tr>
<td>Electrical Heating</td>
<td>0.9</td>
</tr>
<tr>
<td>Conventional Electricity + GSHP</td>
<td>0.27 – 0.20</td>
</tr>
<tr>
<td>Green Electricity + GSHP</td>
<td>0.00</td>
</tr>
</tbody>
</table>

*Table 1: Emission Levels of Different Heating Systems [1].*
Figure 1 above shows the efficiency of different heating and cooling systems. WaterFurnace is simply a type of GSHP system created by the Water Furnace company that provided this image. Their data shows that the coefficient of performance (COP) of a general GSHP is around 3.5 [4]. This means for every kilowatt of power, the system outputs 3.5 kW of heat. A standard air conditioning unit has a lower COP of 1. This means that the compressor in a GSHP will need much less power to output the same amount of heat. This results in a much lower cost to run a GSHP.

While it is true that GSHP installation costs are higher, the efficiency difference has a quick payback period considering that the life of a GSHP is over 20 years with the heat exchanger coils lasting 50 years or more [5, 6]. Even back in 2009, it was observed that the pay-back period for a ground source heat pump compared to conventional systems was 5 – 7 years [7]. The overall general life of a GHSP is over 20 years. The greater efficiency saves more money each year until the GSHP pays for the difference. It’s important to note that these comparisons are done on a smaller residential scale. If applied to a larger corporation scale, the savings will be significantly larger. For example, in a study done in 1996 – 1997 on a group of 4 schools with about 2000 students total in Lincoln, Nebraska, $144,000 was saved each year. In about 20 years, it is expected that $3.8 million dollars will be saved. The school also used 26% less energy per square foot [7].

To better understand the efficiency and factors that impact a GSHP, this system was developed to simulate the sink of a heat pump. The system measures the change in temperature as water held at a constant temperature flows through a copper pipe in water and in soil at various saturation levels. Using this data, the heat transfer rate was compared at these conditions. The data will be used to gain a better understanding of how consequential the pros and cons are for having a heat pump under certain conditions. The data can be applied to a larger scale, to grasp the impact that the surrounding conditions can have on heating and cooling costs.

One important application for this research is educational. This system is being developed for academic purposes in a laboratory setting. It will assist in teaching undergraduate level students the basics of heat
transfer and thermodynamic systems. This system serves as a prototype for the system that will be used in a future class.

**Literature Review**

While it may be clear that using a GSHP is a great option, there is still research to be done on improving the efficiency of the GSHP. What can be done to increase the thermal conductivity? What types of soil are best? Is it better to have saturated or dry soil? Many of these questions have already been answered. Before comparing the research of this paper with the research of others, it’s important to give a general explanation of how this system differs from others. The biggest emphasis of this research is on the fact that the system is in a controlled environment. There is no dependency on rain or temperature changes. The system is contained in a building with heating and cooling, so there should be very few fluctuations in temperature. The research of others that will be discussed lack either the controlled environment or the same focus of this research. This research should provide quantitative and reliable results that can be reproduced in a general manner anywhere. The results will not be susceptible to error due to weather.

For example, in Leong, Tarnawski, and Aittomäki’s study of the *Effect of soil type and moisture content on ground heat pump performance* several types of soil and levels of saturation are tested. Their experimentation and research puts a large emphasis on the soil type. They determine that sand is a superior conductor of heat when compared to silty clay and silty loam. They come to the conclusion that saturation of soil up to 50% saturation makes a significant change in the heat conduction of soil. Above that level of saturation, the change is much more insignificant [8].

In Leong et al.’s research, the testing and the results are at the mercy of weather patterns. The paper says that "The entire process of heat extraction/deposition is a transient one, due to the weather-dependent ground surface boundary conditions and heating/cooling load [8]." The saturation levels may be changing due to rain. The temperature levels are constantly changing. This constant transient state, allows room for error. While this could reflect realistic conditions and provide data for predicting future performance, it does not provide the best general and consistent data that can be used to predict any situation. The data obtained was for a specific area and its weather patterns. The data that will be provided in this report will fill in gaps of uncertainty that the weather may have caused.

It was also mentioned that, "High heat rejection rates to the ground (cooling mode) had a detrimental impact on the soil thermal conductivity, leading to reduction of the heat transfer [8]." This is an issue that any research in this field needs to consider While the soil that is being measured farther away from the system may, in fact, be saturated, the soil that is closer to the system is heating up and may even be drying out due to the heat being released [8, 9]. During the winter months in Leong et al.’s research, the heat being released may even be melting the frozen soil which could cause further data change. In contrast to Leong et al.’s research, the setup being used in this research has less of an issue with this problem. After every trial, the soil is cooled and the soil saturation checked. With the trials being shorter, the soil should not have significant drying. If the soil drying does become an issue, water can be added. There is no issue with frozen soil because the soil is at room temperature. Again, the difference between Leong et. al.’s research and this research is the controlled environment. Soil temperature and saturation can be controlled and monitored easily.

**Objective**

The objective of this research is to determine the difference in heat transfer rate between water and soil, and to observe the effects of soil saturation on heat transfer in a controlled environment. The general COP values for a heat pump will be calculated for the different heat transfer rates observed. The research will
also be applied in the realm of education. This system will act as a prototype for a future system for the classroom.

**Background and Theory**

**Heat Pumps**

There is a clear benefit to using GSHPs, but it’s important to understand how a heat pump in general works before understanding the importance of a GSHP specifically. A heat pump in general has 4 main components. It makes use of a compressor, condenser, evaporator, and an expansion valve. The goal of a heat pump is to move heat. If the heat pump is cooling an area, it will remove the heat from the area being cooled and transfer that heat into the warmer media being used as a heat sink. If it is heating an area, it does the opposite by removing heat from a warm area and transferring that heat into the area being heated.

Consider the cooling process. The heat pump pumps a refrigerant through an expansion valve. This expansion valve decreases the pressure and the temperature of the fluid. Since the temperature is now lower than that of the medium it is flowing through, there will be heat transfer to the liquid. Heat always moves from a higher temperature area to a lower temperature area. This heat transfer occurs in the evaporator. The refrigerant turns to a gas in this stage. Once the heat is absorbed, it passes through a compressor. This compressor will increase pressure and temperature. The heated gas will enter into a condenser in the area being heated. While in the condenser, the heat will be transferred into the colder area. Once the gas condenses back into a liquid, it will return to the expansion valve to decrease the pressure and temperature once more [10]. This process can be seen below in Figure 2 [10].

Figures 2 and 3 both depict the refrigeration cycle in heat pumps. Step 1 → 2 shows the compression from saturated vapor to superheated vapor. In step 2 → 3, the refrigerant becomes a saturated liquid as it goes through the condenser and outputs the heat to the heat sink. In step 3 → 4, the refrigerant becomes a saturated mixture as the expansion process decreases the temperature and pressure. In step 4 → 1, the refrigerant becomes a saturated vapor again through the evaporator [11], transferring heat to the refrigerant. Figure 2 shows a mechanical diagram of an ideal refrigeration cycle while Figure 3 shows the T-s and P-h diagrams.
Ground Source Heat Pumps

Conventional heat pumps work above ground using air. The heat is either pulled or transferred to the surrounding air. However, this has proven to be an inefficient means of producing or even redistributing heat. When dealing with heat transfer, thermal conductivity must be considered. Thermal conductivity, denoted by "k", is a property that every material has, unique to itself. Thermal conductivity defines how well a material can conduct or transmit heat [12]. Air happens to be one of the worst conductors of heat. This is important because it determines how hard the compressor has to work to transfer enough heat. As the heat transfer rate rises, the compressor needs less power to do the same amount of heat transfer.
Therefore, it only makes sense to seek out a different material in which to place the heat pump. Thus, the rise of the GSHP began. The thermal conductivity of the ground is much higher than that of air. By placing the heat pump in the ground, heat transfer is achieved in a more efficient manner. While the constituents of the soil will always vary from location to location, Figure 4 [12] clearly shows the difference in the thermal conductivity of air versus other materials, some of which could be found in soil. One can see that air has one of the lowest thermal conductivities on the figure.

![Figure 4: Thermal Conductivity Values](image)

Not only does the ground increase efficiency based on an increased thermal conductivity, but the ground conditions throughout the year will assist the GSHP. This can be best explained using the heat conduction equation given below:

\[
Q_{\text{cond}} = kA \frac{(T_1 - T_2)}{\Delta x}
\]

where \( A \) is the area perpendicular to the direction of the heat transfer, \( T_1 \) is the highest temperature, \( T_2 \) is the lowest temperature, \( \Delta x \) is the length through which the heat transfer is taking place, and \( k \) is the thermal conductivity previously mentioned. It is important to note two things. First, as previously mentioned, as the thermal conductivity, \( k \), increases, so will the heat transfer. Second, greater heat conduction occurs whenever there is a greater difference in temperature.

The second observation is crucial when considering the advantages of a GSHP. During the summer, the ground stays cooler than the temperature of the air, yet the temperature of the air being cooled will remain high. If it was an air source heat pump, there would be a lot of stress on the heat pump to get rid of the
heat it removed from the cooled area. However, since the ground is cooler, there will be less strain on the GSHP to transfer the excess heat removed into the cooler ground. However, in the winter this is reversed as the ground stays warmer than the surface air. The GSHP will remove the heat with greater ease and distribute it to the area being heated. This temperature difference between the ground and the air can be significant throughout the year. In as little as 10 ft below the surface, the temperature stays around 54°F year round [13].

To calculate the heat transfer rate in a system, one can also use the following equation:

\[ \dot{Q} = \dot{m}c_p(T_{in} - T_{out}) \]  

(2)

where \( \dot{m} \) is the mass flowrate of the refrigerant, \( c_p \) is the specific heat of the refrigerant, \( T_{in} \) is the temperature into the system, and \( T_{out} \) is the temperature out of the system. This formula is useful because the thermal conductivity is not needed. This equation will be used extensively in the research because all of those variables are known or can be easily measured experimentally.
Apparatus

Heating Reservoir

The heating reservoir is a simple setup. This is the initial step in the process. It is crucial that this step have enough power input to be able to heat the water to a high enough temperature. Initial trials struggled to keep the water around 90°F / 32.2°C. To prepare for the amount of heaters needed, the system was first tested with 2 heaters. The change in temperature was recorded. From this change in temperature, the heat loss was calculated. Even though the heaters are rated for 1150 W, these calculations were done with a conservative 1000 W. Once the heat loss was known, the 2000 W from the 2 heaters was subtracted and the needed additional power input was known. This value gave a general range for how many additional heaters would be needed to run the system.

The container is a 15 gallon, 22in x 28in x 8in Tuff Stuff Products Heavy Duty Oval Stock Tank with part number KMT103. It can be bought from multiple vendors. It is made of 100% recycled LDPE flexible plastic, and has proven through multiple trials to be able to withstand temperatures over 100°F. The water was never boiled, however. While the container never showed signs of damage from the heat, one should be cautious when using heat above the tested range of 100°F until more about the temperature limit is known.

The container is divided into three sections by dividers made of the plastic from a tote tank. These tanks are made from high density polyethylene [14]. The dividers were attached with screws. It was sealed with various materials. However, these sealants still failed to make it fully water proof. Water still leaks through the divider but causes no issue. The dividers were made to force the water to flow in a certain pattern. The water needs time to heat completely. If there are no dividers, there is a possibility that the water could flow immediately from the inlet of the container to the outlet without remaining in the container for any significant time. The dividers force the water to go under a divider, over the next, and under another before finally exiting the container. When the system is running with its maximum amount of heaters, all water will be forced to flow by 4 heaters. With the flow rate being approximately 5-gpm at full speed, the water should remain in the container for around 2 minutes. In that amount of time, the temperature will need to be increased up to 8°C for some trials.

Safe-Hete Portable Electric Water Heaters are used to heat the system. Quite a few different heaters were considered. Something as simple as a fish tank heater was once considered, but most of those heaters are not designed for high temperatures. Since we have to heat water several degrees in a short amount of time, it was necessary that the heaters output quite a bit of power. The heaters used are rated for 1150W/120V. Each heater was tested by a Gardner Bender brand PM3000 Power Meter. None of the heaters maintained 1150 Watts. However, the general range was 1070 – 1100W. When calculations were being done to determine the amount of heaters needed, 1000W was used. The heaters simply plug into a 120V outlet. The manual claims that the heaters pull 10 amps. The heaters are using so much current that an alarm went off in the lab when more than 4 heaters were used. A fuse was also blown once when a heater and the pump were plugged in on the same outlet. These heaters are powerful and should be used with caution. Never use them alone. The heater can be seen in Figure 5 below.
The only safety mechanism that the heaters have is an internal thermal protector that disconnects power if the heater is used outside of the water for 2-3 minutes. The heaters do not have any thermostat on them. They will keep outputting heat until they are unplugged. Therefore, it is crucial that they are not left on in stagnant water with no supervision. These heaters are capable of boiling water. The heaters should not be left unattended unless the user is sure that the temperature will not rise to excessive levels.

In trials where the temperature was held constant, thermostats were needed. Model ITC-308 Plug and Play Temperature Controllers from Inkbird were used. These thermostats measure the temperature through an external thermocouple that can be placed anywhere in the water to get a reading. The manual claims to have an accuracy of ± 1°C or 1°F. For the trials with the largest temperature change, 4 heaters with 4 thermostats were needed to maintain around 90°F / 32.2°C. Figure 6 below shows the thermostat used. Take note that the use of the thermostats is most likely what caused the system to blow a fuse in one trial. When the thermostat turned on, it most likely caused a surge of energy that blew the fuse.
Sink
The sink is made up of a 100 gallon, galvanized steel with a heavy duty zinc coating trough. The trough is 4 x 2 x 2 ft in dimension. 100 ft of ACR copper pipe is coiled into two large coils that hang suspended in the tank. The trough and coils can be seen in Figures 7 and 8 respectively below.

The ½ HP Wayne Utility Pump, shown in Figure 9 below, pulls the water from the heating reservoir and pumps it into the copper pipes inside of the heat sink. The ¾ in. PVC runs from the pump into bulkhead fittings which connect to the copper pipe. These bulkhead fittings keep the tank from leaking if it is filled with water. There is a ¾ in. globe valve after the pump that allows one to control the flow rate of the water. This valve can turn 5 times before it is closed. When anything in this report refers to something as 4.75 closed it is referring to how many turns the valve was turned. Therefore, it means that the valve was turned approximately 4.75 rotations to decrease the flow rate.
The heat sink sits on a platform with wheels. It is important that the system be easy to maneuver. The system is large and has many wires connected to it. In many situations it may get in the way and have to be moved. Once water is added to this system, it will be too heavy to move without wheels. In most cases, there should always be at least two people moving the system. When water is involved, it can be difficult or messy if only one person is moving it.

Fafard® 52 Mix Metro-Mix® 852 was used for the soil. This is a potting soil designed for high water drainage [15].

**Flowmeter**

A Hall Effect Flow Meter was purchased from Omega to measure the flow rate of the system. It is model FTB4607. It is rated for a flow rate range of 0.22 – 20gpm (gallons per minute). It is important to note that the flowmeter is only rated for 190°F. While the system should never be this hot, the user needs to be careful not to pump any water nearing a boil because it could damage the flowmeter. The sensor releases 75.7 pulses per gallon. The sensor requires a 6 – 16 VDC power source. The power source used on the system was adjusted to 10 VDC.

The sensor proved to be difficult to connect to LabVIEW. LabVIEW was never capable of reading the signal. One possible reason is that the signal coming into LabVIEW was just too small. The maximum frequency being outputted by the sensor was calculated to be 25.23 Hz. Originally, this sensor was connected to a 5B-Backplane that had a 5B47 conditioning module with a scaling factor of 100 that outputs a range of 0 – 5V for every 0 – 500Hz. Since the frequency input was so small, the output coming through the conditioner may have been too small for LabVIEW to recognize. If this is the issue, a conditioning module using a lower range might fix the issue.

Since LabVIEW never worked with this sensor, an oscilloscope was used to measure the frequency directly. The diagram for the flowmeter is shown in Figure 10 below.
Temperature Measurement
To measure temperature, an NI cDAQ™-9191 from National Instruments was used. This is a CompactDAQ Chassis. It is only compatible with a limited number of sensors such as thermocouples. As the name implies, it is very compact and does most of the work for the user. There is no longer any need for conditioning modules or a DAQ card. It makes use of DAQ assistant function in LabVIEW. This greatly simplifies the programming that goes into the LabVIEW. The chassis can function wirelessly. Due to the lack of internet connection, the chassis was connected to the computer with an Ethernet cable. The setup process is simple and the instruction manual is clear and concise. The thermocouples are connected as Figure 11 shows. A photo of the system can be seen in Figure 12.
Figure 12: NI cDAQ™-9191 from National Instruments

LabVIEW

Figure 13 below is the VI used in LabVIEW to collect data.

![LabVIEW VI](image)

Figure 13: Entire LabVIEW VI

The component responsible for gathering the data is the DAQ Assistant. A closer view of it can be viewed in Figure 14 below. This component connects directly to the CompactDAQ Chassis. As previously mentioned, to access and edit the settings for the thermocouples, right click on the DAQ Assistant and select the Properties options.
The component responsible for keeping track of the time is the *Elapsed Time*. The time outputs from this to the excel sheet. It also connects to a *Greater or Equal? Function* that tells the program to run until it reaches the time inserted by the user into the *Run Time (sec)* controller. There is *Time Passed* indicator connected. A *Stop* button is also connected so that either the trial will end when the time reaches the controlled limit or the *Stop* button is clicked. Figure 15 below shows the *Elapsed Time* connected to the indicators, controls, and first part of the excel sheet. The stop button and excel file portion was taken from a block diagram that the previous design team created for this project.

There are several indicators connected to the data. These indicators show the thermocouple readings. Figure 16 below shows the block diagram for those indicators beside the front panel output.
Figure 17 below shows the portion of the block diagram controlling the output to the excel file. This part was taken from a block diagram created by the previous design team for this project. The pink text boxes in the upper portion of the figure are the column labels. There is also a control for the file name called *Enter File Name*. The green textbox is the location that the excel file will be sent to. These column labels and the location can be easily edited directly from the block diagram.

Figure 17: Output to the Excel File
The main component missing in this VI is the graph. It would be best to add a graph that shows the temperature change over time. This isn’t necessary, but it would give the user a better idea if the trial is going as expected or if there might be any issues.

**Soil Saturation Sensors**

There were two sensors used to measure the soil saturation. The first sensor used was the VH400 Soil Moisture Sensor Probe. The second sensor used was the ecowitt Soil Moisture Monitor With Time Display. It seemed best to have at least two methods to measure the moisture. This helps ensure that if one sensor is faulty, the other will show the error. This concern for error arose when the VH400 Soil Moisture Sensor Probe was first wired up. Upon first testing it, there seemed to be quite a bit of change in the readings that it was outputting. Since these changes were significantly changing the value of the soil moisture values, it seemed necessary to purchase a second sensor to check the output of the first.

The VH400 Soil Moisture Sensor Probe was unnecessarily difficult to get running. While the wiring was relatively simple, it added more wires and mechanisms that had to be used. This only added more time to the setup. There are a couple different ways to get readings from this sensor. The sensor has to be hooked up to something that can measure the voltage readings being outputted. For this research, a multimeter was used. Other things such as an oscilloscope can be used. It was not attempted, but with the output simply being voltage, LabVIEW could probably read and interpret the data as well.

The diagram of how to wire up the VH400 Soil Moisture Sensor Probe can be seen below in Figure 18. There are three wires with this sensor. There is a bare wire with no color. This wire connects to the ground or common of the multimeter, and to the negative terminal of the power source. The ground of the multimeter is usually a black wire. The red wire connects to the positive terminal of the battery. The black wire connects to the input of the multimeter which is normally a red wire. The multimeter should be set on DC Voltage at either a scale of 20 or 200 [16]. All of this wiring information can be found on the vegetronix website [16]. For this research the scale was normally kept at 20 for better precision.

![VH400 Soil Moisture Sensor Probe Diagram](image)

*Figure 18: VH400 Soil Moisture Sensor Probe Diagram*

The complete details of the VH400 Soil Moisture Sensor Probe can be found in the VH400 Soil Moisture Sensor Probe user manual [17]. The power source being used was set to 10VDC which falls in the needed range of 3.5V – 20VDC for the supply voltage. The manual claims that the accuracy is 2% around room temperature. The output of the sensor is from 0 – 3V. The voltage that displays on the multimeter then has
to be converted to a usable measurement for soil moisture. This is done with the following equations in Table 2 that was obtained from the manual.

Table 2: VWC Conversion Equations

<table>
<thead>
<tr>
<th>Voltage Range</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 1.1V</td>
<td>VWC = 10*V-1</td>
</tr>
<tr>
<td>1.1V to 1.3V</td>
<td>VWC = 25*V-17.5</td>
</tr>
<tr>
<td>1.3V to 1.82V</td>
<td>VWC = 48.08*V-47.5</td>
</tr>
<tr>
<td>1.82V to 2.2V</td>
<td>VWC = 26.32*V-7.89</td>
</tr>
</tbody>
</table>

However, it should be noted that these equations do not exceed 50% volumetric water content (VWC). VWC is simply a ratio of the water volume to soil volume [18]. Therefore, this sensor is limited to any applications above this mark. There is a graph that can be found in the manual that can also give VWC values, but it is also capped at 50%. This need to have values above 50% is yet another reason that another sensor was required.

The ecowitt Soil Moisture Monitor With Time Display was much simpler to setup. Its model number is WH0291. This sensor has a range of 0 – 100% unlike the other sensor. The sensor also has a way to calibrate it if the readings appear to be incorrect. The instruction manual states that certain soils could need calibration. The sensor functions off of 2 AA batteries. It should automatically connect when everything is powered up. It can keep time and will output the soil moisture as a percentage to the display. While there was some slight differences in readings from this sensor to the other, they were within 10%. The differences were small enough that no calibration was attempted. One sensor had to be replaced at one point with an identical sensor. As with the sensor it replaced, the new sensor was not calibrated. If this second sensor was reading differently at all, it may have introduced some error for the soil saturation levels for the wet soil trials.

Cost
If built new, the cost of the system can vary considerably depending on the type of materials used. There is considerable variation that can be used in reference to supplies such as thermocouples, flowmeters, containers, etc. Table 3 below shows the cost of the supplies used in this system and the estimated total cost.
Procedure
When the computer is powered on, make sure that the chassis is also plugged in and has power. The chassis should automatically connect and be ready to run upon pulling up the VI. However, sometimes it does not connect automatically. To deal with this issue, search for and select NI MAX on the computer. Select Devices and Interfaces from the choices present. Choose Network Devices from the first drop down list. Choose the chassis that you are using from the second drop down list. Choose the self-test option that comes up. Once this self-test option runs without issue, then the system should be correctly connected. If the self-test fails, it is likely that the system is still unplugged or has not had enough time to connect after being powered up. Wait a minute or two and try the self-test again after pressing refresh.

To check and make sure everything is working correctly, one can select the DAQ Assistant in the LabVIEW program seen in Figure 14 in the Apparatus: LabVIEW section below in the report. Select the Properties option. This will bring up all the settings for the chassis. One can run it from here in order to make sure all the thermocouples are working correctly. If the chassis is not providing a signal, there will be an error message. In this case, complete the process mentioned in the previous paragraph until it is working properly.

Type the length of time that the trial will be run in the Run time (sec) text box. Type the name of the file into the Enter File Name textbox.

Connect the flowmeter to the oscilloscope as shown in the Apparatus: Flowmeter section. Once the system is started, the oscilloscope will begin reading a square wave frequency. To figure out the flow rate, first record various frequency readings throughout the trial to get an average frequency. Divide the frequency by 75.7. This is done because there are 75.7 pulses per gallon. The frequency is in pulses per second. The calculations for obtaining flowrate in gallons per minute (gpm) can be seen below:

\[
\frac{\text{Number of pulses}}{1 \text{ s}} \times \frac{1 \text{ gallon}}{75.7 \text{ pulses}} \times \frac{60 \text{ s}}{1 \text{ min}} = \text{flowrate (gpm)}
\]  

(3)

\[\text{Table 3: Cost of the System}\]

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Item</th>
<th>Unit Price</th>
<th>Total Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Thermocouple</td>
<td>$ 40.00</td>
<td>$ 160.00</td>
</tr>
<tr>
<td>4</td>
<td>Water Heater</td>
<td>$ 52.97</td>
<td>$ 211.88</td>
</tr>
<tr>
<td>1</td>
<td>100 Gallon Trough</td>
<td>$ 104.87</td>
<td>$ 104.87</td>
</tr>
<tr>
<td>1</td>
<td>15 Gallon Heat Reservoir</td>
<td>$ 30.00</td>
<td>$ 30.00</td>
</tr>
<tr>
<td>4</td>
<td>Thermostat</td>
<td>$ 36.00</td>
<td>$ 144.00</td>
</tr>
<tr>
<td>1</td>
<td>Soil Moisture Sensor</td>
<td>$ 39.95</td>
<td>$ 39.95</td>
</tr>
<tr>
<td>1</td>
<td>Flow Meter</td>
<td>$ 219.39</td>
<td>$ 219.39</td>
</tr>
<tr>
<td>1</td>
<td>100 ft. of 1/2&quot; ACR Copper Pipe</td>
<td>$ 132.19</td>
<td>$ 132.19</td>
</tr>
<tr>
<td>1</td>
<td>NI cDAQ™-9191 from National Instruments</td>
<td>$ 439.00</td>
<td>$ 439.00</td>
</tr>
<tr>
<td>1</td>
<td>Water Pump</td>
<td>$ 152.17</td>
<td>$ 152.17</td>
</tr>
<tr>
<td>1</td>
<td>4x Caster wheels</td>
<td>$ 23.00</td>
<td>$ 23.00</td>
</tr>
<tr>
<td>1</td>
<td>Miscellaneous</td>
<td>$ 200.00</td>
<td>$ 200.00</td>
</tr>
<tr>
<td></td>
<td>Total Project Cost</td>
<td></td>
<td>$1,883.44</td>
</tr>
</tbody>
</table>
If needed, connect the soil moisture sensors as shown in the Apparatus: Soil Saturation Sensors section. Before starting, measure the temperature of the media being tested to make sure it is around room temperature. Once everything is connected, power up the needed heaters. Mix the water until the heaters are near 32.2°C or 90°F. Keep in mind, that at the start of the trial, there will be an immediate drop in temperature due to the cold water in the pipes. This will alter the inlet temperature for a few minutes until the heaters are able to catch up. To minimize this drop, one can overheat the heating reservoir a few degrees.

To begin the trial, start the pump and the VI. Allow the trial to complete its time or stop it early, if necessary. Regardless, the data will be exported to an excel file in whatever location it was previously programmed to export to.
Results and Discussion

Water

Some of the first data gathered was on water. Figure 19 shows a trial with water functioning as the heat sink.

![Figure 19: Trial 1 Graph of Temperature vs. Time with Water at Maximum Flowrate with Thermostat](image)

The flow rate was at maximum value. For this trial, the flowrate was 4.84-gpm or 0.305 kg/s. Note how the graph is steeply dropping in the first 200 seconds. It isn’t until around 200 seconds that the system begins to reach steady state. This drop is coming from the fact that the heaters are unable to provide enough power initially. 100 seconds into the trial, the system is still losing 5.7 kW based on the temperature change between the inlet and outlet. There are only 4 heaters in the system, each of which are rated for 1.15 kW. The pump is also putting in some undetermined amount, but it is not enough to keep the drop from happening. It is a ½ hp pump which converts to 372.85 W. This drop is more extreme due to the use of the thermostats. Once the thermostats sense that it is hot enough, they will turn the heaters off. This most likely means that the two heaters in the front of the heating reservoir are constantly running as the colder water enters while the two at the end are shut off as the warm water leaves. This creates a sharper drop in temperature because not all of the heaters are heating the system. The other drops and irregularities in the temperature throughout the trial are coming from the thermostats turning on and off. These irregularities are most noticeable around 1500 – 1700 sec. These irregularities can be attributed to the thermostats because when the thermostats are removed, the data looks like Figure 20 below where the data is smooth without any drops in temperature. Any irregularities at the very beginning of any of these trials before the steady drop or rise in temperature is due to the cold water filtering out of the pipes. In this trial, the impact of the cold water can be seen in how the outlet temperature jumps from around 21°C to 30°C in about 16 seconds.
One of the most important parts of the data without thermostats is after that 200 second mark. From here, one can observe the heat sink gradually heating up and how this impacts the heat transfer rate. There is an inverse relationship between the two factors. As the heat sink heats up, the heat transfer rate decreases because the change in temperature is less. This data could be easily applied to an undergraduate lab to display the concepts of heat transfer.

When observing the data for when thermostats are not included shown in Figure 20 below, the same observations can be made. There are no spikes in temperature because the thermostats are not turning on and off. The flowrate was 4.91-gpm or 0.309 kg/s. The most important data for understanding the concepts of heat transfer takes place in the first 500 seconds. The data after the drop to steady state is less useful because it is unbounded and simply shows a rise in temperature. The slope downward as the system was balancing out is more gradual because the heaters are outputting maximum power without the thermostats. By observing where the line reaches steady state, one can determine approximately how much power the system is putting out. In this trial, the temperature significantly slows in its decreasing trend around 32.4°C around 250 seconds. At this point, the heat transfer rate is 4.95 kW. This means that the heaters and pump are outputting nearly that much power. However, the system does not bottom out in temperature until around 420 seconds at about 32°C. At this point, the heat transfer rate has dropped to about 4.38 kW. This is what one would expect from heaters rated at 1.15 kW each. This slightly lower power comes from the fact that most of the heaters, when tested, actually outputted 1.07 – 1.10 kW instead of the 1.15 kW. This is clear and observable data showing when the system’s heat transfer rate balanced with the power input of the heaters and pump. While this is expected data, it can provide discussion topics and objectives for an academic lab.

![Figure 20: Trial 1 Graph of Temperature vs. Time with Water at Maximum Flowrate Without a Thermostat](image-url)

Referring back to the trials with thermostats, the same general observation is there. One can see the system bottom out around 31.9°C around 340 seconds. The heat transfer rate at this point is 4.37 kW. This bottom point did not occur right when the heaters turned on. The system gradually dropped until that 340
second mark. This could have been due to low thermostat precision or it could have been that the heat transfer rate was still 5.14 kW at 200 seconds. 5.14 kW is more than the heaters could support. The other two trials with thermostats didn’t have this same slow temperature drop. The graphs for these trials can be seen in the Appendix in Figures 22 and 23. When the thermostats kicked on to start heating the system, the heat transfer rate was already near what the heaters could support. Trial 2 was already below 4 kW and trial 3 was right around 4.5 kW. This lower heat transfer rate could have been due to a couple different things. The sink was a few tenths of a degree cooler for the first trial. This should have had minimum impact. The main difference is that the trial 1 inlet temperature was still hotter than the other trials. This is why that trial continued to drop a little more while the other trials had already begun to fully balance out. This higher heat transfer rate and delayed balancing is probably due to the fact that trial 1 started with a hotter reservoir of at least 1°C.

The following Table 4 shows the heat transfer rates when the system reached a balanced steady state. An average was taken for about 50 seconds of data. If too large of a data range is used, the heat transfer rate will decrease as the sink temperature increases. These lower heat transfer rates are listed as the Final Average Heat Transfer Rate in the table. The ranges for these were less specific and simply took an average near the end to show how the heat transfer rate did decrease.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Average Flow Rate (gpm)</th>
<th>Average Flow Rate (kg/s)</th>
<th>Steady State Average Heat Transfer Rate (kW)</th>
<th>Final Average Heat Transfer Rate (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Water Fully Open with Thermostat</td>
<td>4.841</td>
<td>0.305</td>
<td>4.413</td>
<td>3.218</td>
</tr>
<tr>
<td>2 Water Fully Open with Thermostat</td>
<td>4.899</td>
<td>0.309</td>
<td>4.020</td>
<td>2.066</td>
</tr>
<tr>
<td>3 Water Fully Open with Thermostat</td>
<td>4.985</td>
<td>0.314</td>
<td>4.098</td>
<td>2.203</td>
</tr>
<tr>
<td>Average</td>
<td>4.908</td>
<td>0.309</td>
<td>4.177</td>
<td>2.496</td>
</tr>
<tr>
<td>1 Water Fully Open without Thermostat</td>
<td>4.909</td>
<td>0.309</td>
<td>4.447</td>
<td>3.931</td>
</tr>
<tr>
<td>2 Water Fully Open without Thermostat</td>
<td>4.826</td>
<td>0.304</td>
<td>4.472</td>
<td>3.875</td>
</tr>
<tr>
<td>3 Water Fully Open without Thermostat</td>
<td>4.874</td>
<td>0.307</td>
<td>4.367</td>
<td>3.924</td>
</tr>
<tr>
<td>Average</td>
<td>4.870</td>
<td>0.307</td>
<td>4.429</td>
<td>3.910</td>
</tr>
</tbody>
</table>

Wet Soil

Figure 21 below shows the only valid trial for the mostly saturated soil at a maximum flowrate of 4.81-gpm or 0.30 kg/s. The soil moisture content was 89%. These trials were only run with 2 heaters since the heat transfer rate was less. At times, even the pump has enough power to heat these systems. Therefore, sometimes less heaters are used to caution against overheating. Even in this graph, one can see that the inlet and outlet do increase slightly overtime as it overheats.
Figure 21: Trial 2 Graph of Temperature vs. Time with Wet Soil at Maximum Flowrate

It’s important to state that the data for this trial is somewhat questionable. The trial shown in the graph seems to record the inlet and outlet temperature correctly, but the sink is not moving. Based on other data gathered, the sink near the coil should heat up. The most likely reason for this is that the thermocouple was still placed too far from the coil. If it is too far from the coil, it could go the entire trial without heating up.

As one can see on the graph, the system is balancing out more gradually with the wet soil than it did with the water. The water was such a great heat transfer agent that it had a quick, steep balancing period. The wet soil creates a much lower heat transfer rate, so the slopes should not be as steep. However, because this trial did not have an overheated heat reservoir at all, and was balancing out by heating up, it is difficult to make the same observations that were made with the water. In this trial, it has less to do with the heat transfer rate with the soil and more to do with the fact that there are only 2 heaters heating the water instead of 4.

As would be expected, other than the initial influx of colder water, the system did not struggle to heat the water. The system reached its peak around 325 seconds at a temperature of 32.9\(^\circ\)C with a heat transfer rate of 0.55 kW. The system reaches a steady state immediately after that peak. The average value for the heat transfer rate for that steady state was 0.29 kW and the final average heat transfer rate was 0.08 kW.

Dry Soil
The following data and discussion is on the dry soil trials at maximum flowrate. Note that the dry soil had no water added but was not completely unsaturated. The ecowitt Soil Moisture Monitor read a constant 36% soil saturation for Trial 1 while the VH400 Soil Moisture Sensor Probe read 34.2% on average. Figure 22 below shows the Temperature vs. Time graph for Trial 1. First, note that the sink does heat up over time for this trial as expected in contrast to the wet soil trial which had very little movement in temperature. This is only a portion of this trial. The full trial can be seen in Figure 24 in the Appendix.
Again, as with the other trials, take note of the initial balancing of the system. At first glance, this trial seems to reach a balance faster. There is an initial drop over the first 420 seconds or so before the system reaches its lowest point. This is still a slower drop in comparison to the water trials. The more important observation, however, is not how fast the temperature dropped, but how low it dropped. The thermostats were set to keep the water at 32.2°C. This trial balanced out at about 35.5°C. This is 3.3°C higher than it is supposed to be. The heaters should all be off. Therefore, the only source of power is coming from the pump. That means that there is very little power going into the system, yet it is still enough to heat the water. This shows how poorly dry soil transfers heat. The average heat transfer rate at steady state was 0.21 kW. This is evidence that the pump is outputting at least this much power to heat the water since the heaters should be off at all times in this trial. Since the ½ hp pump is equivalent to .373 kW, this number is reasonable since not all of that power will be inputted to the water in the pipes. The final average heat transfer rate is a very low 0.07 kW.

At least with the wet soil trial previously discussed it initially held around 32°C. However, these trials were different in the fact that the wet soil trial didn’t start out as hot. The wet soil trial started out closer to 32°C. While the data does support better heat transfer for the wetter soil, to truly compare the two sets of data, another wet soil trial would need to be run starting closer to 37°C. It is still important to note that the wet soil trial did still increase in temperature over time, but it was slower as the heat transfer rate began to decrease. Once the thermostats turn off the heaters in the wet soil trial, the temperature does decrease some over time. This means that initially the pump was not able to heat the water by itself. However, over time, the heat transfer rate decreased enough that the pump caught up and began to overheat the system. This is more data showing that the dry soil is a worse heat transfer agent since the pump immediately started heating the system up.

Table 5 below shows the flowrates and heat transfer rates for the two trials run at these conditions.
Table 5: Average Heat Transfer Rates for Mostly Unsaturated Soil

<table>
<thead>
<tr>
<th>Trial</th>
<th>Average Flow Rate (gpm)</th>
<th>Average Flow Rate (kg/s)</th>
<th>Steady State Average Heat Transfer Rate (kW)</th>
<th>Final Average Heat Transfer Rate (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Dry Soil Fully Open with Thermostat</td>
<td>5.044</td>
<td>0.318</td>
<td>0.214</td>
<td>0.065</td>
</tr>
<tr>
<td>2 Dry Soil Fully Open with Thermostat</td>
<td>5.019</td>
<td>0.316</td>
<td>0.221</td>
<td>0.045</td>
</tr>
</tbody>
</table>

In this dry soil trial the data clearly shows how the temperature next to the coil rose significantly. The fact that the temperature farther from the coil only changed about 0.2°C in 3.5hr shows how slowly the soil transfers heat.

**Lower Flowrate Trials**

The trials involving lower flowrates are less trustworthy due to the fact that the flowrate often decreased throughout the trial. These issues will be discussed further in the *Results and Discussion* section. While the data may not be numerically accurate at all times, the data does still apply qualitatively when compared to the higher flowrate trials. Regardless, the flowrate was much lower compared to the maximum flowrate. Also, note that anytime the term “4.75 closed” is used, it is referring to the positioning of the globe valve.

When it came to the water trials, the heat transfer rate acted as expected. Table 6 below shows the heat transfer rates for the water trials with and without thermostats.

Table 6: Average Heat Transfer Rates for Slower Flowrates

<table>
<thead>
<tr>
<th>Trial</th>
<th>Average Flow Rate (gpm)</th>
<th>Average Flow Rate (kg/s)</th>
<th>Initial Average Heat Transfer Rate (kW)</th>
<th>Final Average Heat Transfer Rate (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Water 4.75 Closed with Thermostat</td>
<td>2.279</td>
<td>0.144</td>
<td>3.320</td>
<td>2.227</td>
</tr>
<tr>
<td>2 Water 4.75 Closed with Thermostat</td>
<td>2.166</td>
<td>0.136</td>
<td>3.653</td>
<td>2.545</td>
</tr>
<tr>
<td>3 Water 4.75 Closed with Thermostat</td>
<td>1.876</td>
<td>0.118</td>
<td>2.972</td>
<td>2.281</td>
</tr>
<tr>
<td>Average</td>
<td>2.107</td>
<td>0.133</td>
<td>3.315</td>
<td>2.351</td>
</tr>
<tr>
<td>1 Water 4.75 Closed without Thermostat</td>
<td>2.101</td>
<td>0.132</td>
<td>4.765</td>
<td>4.319</td>
</tr>
<tr>
<td>2 Water 4.75 Closed without Thermostat</td>
<td>1.681</td>
<td>0.106</td>
<td>4.389</td>
<td>4.185</td>
</tr>
<tr>
<td>3 Water 4.75 Closed without Thermostat</td>
<td>2.236</td>
<td>0.141</td>
<td>4.246</td>
<td>3.927</td>
</tr>
<tr>
<td>Average</td>
<td>2.006</td>
<td>0.126</td>
<td>4.467</td>
<td>4.144</td>
</tr>
</tbody>
</table>

Based on Equation 2, the heat transfer rate decreases for the trials with the thermostat because the flowrate decreased more drastically than the temperature change increased. There is a direct relationship between the flowrate and the heat transfer rate. It may seem odd that the heat transfer rate stayed high for the trials without the thermostats. However, this is because the lack of thermostats allows the upper temperature to be higher. There is not enough flowrate to decrease the temperature below around 34°C in any of the trials. If the reservoir was started closer to 32.2°C, the observed heat transfer rate might be closer to the trials with thermostats. Because this upper temperature is higher, the change in temperature in Equation 2 offsets the decreased flowrate.

The most intriguing results came from the soil trials. Table 7 below shows the heat transfer rates and flowrates for the soil trials.
For these trials, the opposite change happened. Compared to the data for the soil trials at higher flowrates previously mentioned, the heat transfer for these lower flowrate trials was higher. This is the opposite result of the water trials. While the heat transfer rate for the water trials went down, the soil trials went up.

This odd heat transfer rate observation is most likely due to error in the flowrate measurements. For some of the trials, the average flowrate was taken near the beginning of the trial. However, as previously mentioned with the lower flowrate trials, the flowrate decreased over time. This means that the average flowrate used in the calculations may be higher than the flowrate later in the trial. The change in temperature used to calculate the heat transfer rate would have been averaged slightly later in the trial when steady state was reached. Therefore, if the flowrate had decreased by this moment, the change in temperature would be greater. This would cause a larger value for the heat transfer rate since you are taking a higher flowrate and a higher change in temperature. To get the correct value, the flowrate at the change in temperature used would need to be recorded. Take note, however, that even with the errors in the heat transfer rate, the data still qualitatively acts expected with the relationship of dry soil vs. wet soil. The wet soil more than doubles the heat transfer rate of the dry soil.

### Heat Wave

One interesting and unexpected observation was the heat wave created by the heat transfer in soil. Because the soil is a much slower agent of heat transfer, the temperature can be more accurately tracked over a longer period of time. In the early trials using soil, it was unknown how long it would take the soil to cool if it was just allowed to sit in place. Therefore, several trials measuring the cooling period were run. Cooling was done in a couple ways. The most efficient way was to balance out a constant addition of cold water while also constantly removing other water. This creates a constant cold reservoir. Basically, the trials are being done in reverse. If the reservoir is allowed to sit with no new water, the hotter sink and the pump will heat it back up and nothing is accomplished.

However, the interesting data gathered emerged when the temperature was measured overnight for 8.3hr. with no moving water. This provided data on the movement of temperature through the soil. Figure 23 below shows the graph of Temperature vs. Time for this overnight cooling.

### Table 7: Average Heat Transfer Rate for Soil at Lower Flowrate

<table>
<thead>
<tr>
<th>Trial</th>
<th>Average Flow Rate (gpm)</th>
<th>Average Flow Rate (kg/s)</th>
<th>Initial Average Heat Transfer Rate (kW)</th>
<th>Final Average Heat Transfer Rate (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Mostly Unsaturated 4.75 Closed with Thermostat</td>
<td>2.409</td>
<td>0.152</td>
<td>0.243</td>
<td>0.130</td>
</tr>
<tr>
<td>3 Mostly Saturated 4.75 Closed with Thermostat</td>
<td>2.158</td>
<td>0.136</td>
<td>0.563</td>
<td>0.294</td>
</tr>
</tbody>
</table>
Note how the heat sink temperatures completely change spots over time. The thermocouple near the copper coil in the sink started at 26.9°C and ended at 24.6°C while the thermocouple far from the coil went from 24.6°C to 25.9°C. This change in temperature is data showing the slow motion of a heat wave throughout the system. The reason that the two sink temperatures did not balance out with each other is most likely due to the fact that all the heat was converging on that one thermocouple far from the coil in the center of the ring. Heat was radiating towards it from all directions. This would cause its temperature to rise more than expected if the only heat coming toward it was the heat located at the thermocouple by the coil. This could be valuable data to demonstrate transient heat transfer over a certain distance for an academic lab.

Heat Transfer Rate Comparison
The most valuable and reliable data for this research came from the trials running at maximum flow rate. Table 8 below shows the averaged values of all of the reliable data gathered at the maximum flowrate with thermostats.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Average Flow Rate (gpm)</th>
<th>Average Flow Rate (kg/s)</th>
<th>Steady State Average Heat Transfer Rate (kW)</th>
<th>Final Average Heat Transfer Rate (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>4.908</td>
<td>0.309</td>
<td>4.177</td>
<td>2.496</td>
</tr>
<tr>
<td>Wet Soil</td>
<td>4.806</td>
<td>0.303</td>
<td>0.290</td>
<td>0.082</td>
</tr>
<tr>
<td>Dry Soil</td>
<td>5.031</td>
<td>0.317</td>
<td>0.217</td>
<td>0.055</td>
</tr>
</tbody>
</table>

The data shows that the water was, as expected, a much greater heat transfer agent. Every trial came out above 4 kW with the maximum being 4.413 kW. The dry or mostly unsaturated soil was much lower at an average of 0.217 kW. When the soil was saturated, the heat transfer rate went up to 0.290 kW. This supports the expected results that the water would be the best heat transfer agent with the soil improving as the soil became more saturated. This is due to the fact that, when unsaturated, the air takes the place of water in the soil. With air being a worse conductor of heat, the heat transfer rate decreases as the saturation level decreases.
In an attempt to get an idea of the efficiency of the water and each soil saturation, $\dot{Q}$ can be related to \(\text{COP}\) with the following relation:

$$\text{COP} = \frac{\dot{Q}_L}{\dot{W}_C} = \frac{\dot{Q}_L}{1}$$

(4)

where $\dot{Q}_L$ is the heat being pulled from the heat reservoir to the soil and $\dot{W}_C$ is the work of the compressor. Since there is no compressor in this system, it can be held as a constant of 1. The COP can then be compared by observing the differences in $\dot{Q}$. Just from the average dry soil heat transfer rate to the saturated soil, there is a 33.6% increase in the COP. From the saturated soil to the average water heat transfer rate, there is a 1340.3% increase in the COP. This is undeniably better. These values, as well as the method for calculating them, should be verified further in the future.

Take note from Table 8 that for the all the trials, including the water trial, the heat transfer rate decreases by the end. This is easily accounted for. As the system runs, more and more heat is dispersed to the heat sink. When this happens, the sink begins to heat up. Once the sink heats up, less heat will be discarded which will result in a lower change in temperature and, therefore, a lower heat transfer rate. This drop in the heat transfer rate is less when the thermostat is not used. This is due to the fact that both the heat sink and the heating reservoir are getting hotter. This will allow a lot of heat to still be discarded to the sink even though the sink is still hotter than before. Unless one was dealing with a very small sink where the water could not stay cool, water is going to be the superior heat transfer agent in almost every case.

**Data Concerns**

It is important to reiterate the fact that the flowrates are questionable. They were not checked for calibration initially. When the flowrate was at a maximum, it was near constant at 5gpm for most of the trials. As mentioned in the *Apparatus: Flowmeter* section, the flowmeter was connected to an oscilloscope that measured the frequency. The frequency was converted using a relation found in the manual [20] for the flowmeter. This relation was checked by using a bucket catch method. This involves catching the water with a bucket and checking the weight. It was a crude method, but the highest percent difference was 5.8%. These results could probably be improved if an electronic scale with higher precision was used to weigh the water. It appears that the maximum flowrate can be trusted. The lower flowrate was tested with two trials with the maximum error being 1.1%. However, the lower flowrates changed throughout each trial. While the conversion rate may be correct, the value did not stay constant throughout the trial. This data is less trustworthy.

The standard for thermocouple error is $\pm 2.2^\circ C$ or 0.75%. Whichever is larger is considered the error [22]. This is concerning for the data gathered. There were some observations made with temperature differences less than 1$^\circ C$. While the error is considerably higher than the ranges being observed, the data and analysis does make sense, but should be accepted with caution.
Conclusion

The data showed that water was, by far, the superior heat transfer agent with an average heat transfer rate of 4.177 kW. This is a 1340.3% increase in COP from saturated soil at 0.290 kW. The soil increased by 33.6% in COP from the average heat transfer rate of the dry soil at 0.217 kW. This agrees with the data found in Leong et al.'s research of a 35% decrease in COP from wet soil to dry soil [8]. The reliability of the data is further supported by the steady state value of the heat transfer rate in comparison to the power output of the heaters and pump. The heaters are rated for 1.15 kW each and were measured to output slightly less than that. The pump also proved to output at least 0.21 kW since it began heating up the water by itself in the dry soil trial. This means that the heaters should be able to maintain a system at 32.2°C whenever the heat transfer rate is around 4.45 kW. The water trials support this since they all leveled out around 4.37 – 4.5 kW.

There are many things that can be done to improve the quality of this data. The sink size needs to be increased if data over a longer period of time is desired. At this point, the sink is heating up over time and decreasing the efficiency of the system. However, for academic purposes, this would result in shorter trials for a lab and would demonstrate issues that a heat sink might introduce with an actual heat pump. It would be beneficial to keep track of the power input to the heaters. At this point, the thermostats are going on and off unchecked. There is no way to record how long the heaters are on or off or how much power they are outputting. To get an even more accurate view of power input into the system, it would be best to measure the temperature change on each side of the pump. The data shows that the pump is impacting the temperature change, but it is unclear how much heat it is introducing to the system. By measuring the change in temperature, one could calculate the heat transfer occurring at the pump. The data would also be significantly improved if the length of the copper piping was increased to increase the change in temperature.

For academic purposes, it would be useful to make sure that the heating reservoir was always a little hotter than it needed to be. This allows the system to cool down to steady state when it first starts which shows how well the heat transfer takes place. This observation was seen in several of the trials for this research, especially the water trials. However, not all of the trials were started off hotter. This made it more difficult to make this observation since not all trials could be compared. By starting a little hotter, students could observe the difference in the speed of the heat transfer rate.

The soil had several issues with it. It contained organic material that began to mold overtime when it sat in water. After a while the soil began to smell badly. The soil also had very bad heat transfer properties. Based on Figure 4 certain types of organic material such as wood have a very low thermal conductivity. The soil being used had wood chips in it. It is expected that other types of media may prove to have better heat transfer properties. Sand may be an easier media to work with that would give better results according to the research of Leong et al. The soil was potting soil and probably allowed many air pockets for drainage. Working with the soil was also difficult. It clogged up the drainage which caused a lot of issues when trying to cool the soil.

To avoid the irregular movement in temperature that several of the trials had, the thermostat thermocouples need to be placed more carefully. This irregular movement can be seen in Figure 19 for the water trials at maximum flowrate with thermostats. These irregular movements are most likely due to the fact that some of the thermostat thermocouples were placed directly into the outlet of the system. This means that those heaters are often going to constantly run since that outlet is the coldest part of the system. To avoid this, the thermocouples should be suspended more evenly in the actual reservoir. It is
important to leave plenty of space between the thermocouples and the heaters in order to get an accurate reading.

There are quite a few smaller recommendations that would improve the efficiency of the process and quality of the data. For one, a flowmeter that can work in unison with the thermocouples would be very useful. The current flowmeter never correctly connected with LabVIEW and caused several more steps in reading the flowrate. If a flowmeter could be used with LabVIEW, an oscilloscope would no longer be necessary and the overall clutter of the system would be decreased. The container for the heating reservoir should also be replaced. The dividers in the reservoir for forcing the water to be heated are not water tight. It may be useful to purchase a container with vertical sides that can have the dividers epoxied or even welded to the container. Another type of valve besides a globe valve should be tested. For whatever reason, the lower flowrates would decrease overtime. The cause of this is most likely either in the globe valve or in the pump itself.
Appendix

**Figure 24**: Complete Trial 1 Graph of Temperature vs. Time with Dry Soil at Maximum Flowrate

**Figure 25**: Trial 2 Graph of Temperature vs. Time with Water at Maximum Flowrate with Thermostat
Figure 26: Trial 3 Graph of Temperature vs. Time with Water at Maximum Flowrate with Thermostat

Figure 27: Trial 2 Graph of Temperature vs. Time Water at Maximum Flowrate Without a Thermostat
Figure 28: Trial 1 Graph of Temperature vs. Time Water at Maximum Flowrate Without a Thermostat

Figure 29: Trial 1 Graph of Temperature vs. Time Water at Lower Flowrate With a Thermostat
Figure 30: Trial 2 Graph of Temperature vs. Time Water at Lower Flowrate With a Thermostat

Figure 31: Trial 3 Graph of Temperature vs. Time Water at Lower Flowrate With a Thermostat
Figure 32: Trial 1 Graph of Temperature vs. Time Water at Lower Flowrate Without a Thermostat

Figure 33: Trial 2 Graph of Temperature vs. Time Water at Lower Flowrate Without a Thermostat
Figure 34: Trial 3 Graph of Temperature vs. Time Water at Lower Flowrate Without a Thermostat

Figure 35: Trial 2 Graph of Temperature vs. Time Dry Soil Fully Open With a Thermostat
Figure 36: Trial 1 Graph of Temperature vs. Time Dry Soil Lower Flowrate With a Thermostat

Figure 37: Trial 1 Graph of Temperature vs. Time Saturated Soil Lower Flowrate With a Thermostat
References
